Experimental Fracture Assessment Diagram by Ultimate Crack Resistance

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Abstract. The report is devoted to application of the two-parameter fracture criterion to experimental results for the specimens with cracks. Tension specimens were cut out from the defective rolled steel plate with stratifications in the middle of its thickness. The plate thickness is 100 mm and the length of the specimens is same. In the middle of specimens there were cracks of different shapes and sizes which were measured after specimen fracture. The maximum critical (fracture) load was recorded. For each crack configuration, at a known fracture load, there were critical stress intensity factors. Crack sizes, fracture loads and character of fracture for all specimens were different. Therefore critical stress intensity factors are also different. By the definition, these factors are called the ultimate crack resistance [Morozov, 1968]. Dependence of the ultimate crack resistance on the fracture stress is called the failure assessment diagram (two-parameter fracture criterion). Experimental points well correspond to approximating function proposed earlier. Comparison of the ultimate crack resistance approach with the failure assessment diagram given in Document R6 showed considerable conservatism of the R6 crack resistance estimation.

Introduction

During last few years, two-parameter fracture criteria were introduced in the form of one common relation to describe both brittle and ductile fractures including intermediate fracture conditions. These criteria are especially useful in the case of calculation of allowable crack length when fracture conditions are different for different crack lengths.

In this paper, the ultimate crack resistance concept is considered due to its universal and multipurpose character.

In 1966-1968, the two-parameter fracture criterion was formulated in updated notation as follows [1-3]:

$$\left(\frac{p \le p_c}{p_u}\right)^q + \left(\frac{K \le I_c}{I_{c\max}}\right)^2 \le 1 \qquad (1)$$

where p and p_c are load parameter and its fracture (or limiting) value, p_u is a load parameter for specimen without a crack, K is the stress intensity factor, I_C is the ultimate crack resistance. The sum in the left-hand side of Eq. 1 equals to 1 when $p = p_c$ and $K = I_c$. When Eq.1 has equality sign it expresses a failure assessment diagram.

Later, another two-parameter criterion was offered by Dowling and Tawnley in 1975 [4].

From Eq. 1 the traditional form of strength condition follows:

$$K \le I_c \tag{2}$$

where $I_c = I_{c\max}\sqrt{1-\left(p_c/p_u\right)^q}$ is an analytical expression for ultimate crack resistance I_c. Here I_{cmax} and q are empirical values (in many cases $q = 2,...,4$).

From Eq. 2 it follows that the stress intensity factor K (SIF) should not exceed the ultimate crack resistance I_c, which is regarded as a function of fracture load parameter p_c , but not a constant value. The case of fracture accompanied by plastic deformation leads to complication in the right (experimental) part of the strength criterion, but the left (calculated) term stays in usual Irwin's notation. Some methods of material properties estimation and strength calculation are presented in studies [5-6].

The ultimate crack resistance

The ultimate crack resistance I_c is an experimental value. A set of full-scale specimens or specimens with similar shape should be tested for the ultimate crack resistance determination. It is desirable to imitate an external loading and to set the maximum value of the load parameter p_c. All specimens should be of same size but with different crack lengths. One or several specimens should be manufactured without cracks for determination of parameter p_u. All specimens are tested to fracture with recording maximum fracture load (or another load parameter). The initial crack length can be defined after complete fracture. No other measurements are required. As a result of performed experiments the fracture load value p_c is determined for a corresponding crack length l. The stress intensity factor K can be calculated for all specimens with given fracture load p_c, initial crack length and other specimen sizes.

Such approach allows considering nuances of behavior of a cracked structural component and considerably improves reliability of strength estimation. It takes into account real manufacturing conditions and technical features. Sometimes, it makes experiments much easier using appropriate computer modeling. It is suitable for a mass production design, or on the contrary, for unique design, such as in cases of nuclear pressure vessels and oil-gas processing apparatuses.

Experiments

The following experiments have been made. A sheet of rolled steel rejected at plant (a steel 09Г2С), intended for manufacturing of a tube was taken and 27 samples of defective metal were cut out. The defects of the rolling sheet were detected by the ultrasonic method and identified as numerous stratifications located in a median plane of the rolling sheet. The thickness of the rolling sheet was 100 mm. It allowed cutting out specimens with cross-section 4÷6 by 23÷33 mm and length 100 mm in such a manner that the defects (stratifications) were in the middle of samples and axes of the sample were perpendicular.

Separately, mechanical properties were determined using standard samples: a yield stress - 360 МПа and an ultimate strength - 540 МПа.

Further, tension tests were performed for estimation of fracture gross-stress in the samples containing real defects - stratifications. Sizes and an arrangement of stratifications were specified on the basis of the analysis of a sample flow surface.

During experiments, video recording was conducted, allowing determining the moment of a fracture initiation, and a defect in which this fracture arose. In general, fracture of samples had ductile-brittle character. Ductile fracture was observed in samples with small defect sizes. Samples with large defects were fractured in a quasi-brittle manner and, nevertheless, with appreciable necking in thickness direction.

In this case it is appropriate to use the two-parameter fracture criterion. The two-parameter fracture criterion gives a possibility to describe both brittle and ductile fracture only by means of SIF.

Following the proposed criterion, the stress intensity factors were calculated for the maximum defects in samples. Thus all defects visible on a flow were reduced to eight crack types. Results of SIF calculation for defects at gross-stress, matching to the rupture moment and the fracture stress are listed in Table 1. By definition, values of the stress intensity factor estimated for the given sizes of cracks are an ultimate crack resistance I_C.

Table 1. Experimental values of the ultimate crack resistance and the fracture stress

Sample	I_C, [MPa·m$^{1/2}$]	σ$_C$, [MPa]	Sample	I_C, [MPa·m$^{1/2}$]	σ$_C$, [MPa]
1	47,27	338,3	15	29,58	499,1
2	51,25	351,9	16	31,8	501,9
3	45,72	356,5	17	32,37	502,2
4	35,2	378,8	18	26,69	503,6
5	42	437,1	19	35,56	504,6
6	40,3	437,1	20	25,24	506,5
7	38,58	445,6	21	34,4	507,4
8	34,7	452,2	22	29	510,1
9	36,7	457,9	23	29,26	513,2
10	42,97	466,2	24	17,9	516,1
11	32.16	477	25	32,65	519,3
12	35,06	488,8	26	23,23	520,5
13	28,4	491,5	27	21,33	528,9
14	35,83	493,6			

Experimental points are put on a co-ordinate plane I_C - σ$_C$ (Fig. 1). Dependence of ultimate crack resistance I_C on the fracture stress σ$_C$ is called the failure assessment diagram (diagram of crack resistance).

It is worth noting that experimental dependence I_C (σ$_C$) can be satisfactory presented by Eq. 1 in the range of small crack lengths by fitting empirical factors $I_{C\ MAX}$ and q. In our case a coefficient of correlation 0.88 corresponds to $I_{C\ MAX}$ = 55 MPa·m$^{1/2}$ and q = 4 (line 1).

Calculations

During equipment design, safety factor $n = \sigma_U / \sigma_1$ is used. This means that the equipment always meets the requirements of the general strength. Safety factor n causes shift of the failure assessment diagram to the left along the stress axis. Presence of crack-like defects in equipment metal requires additional verification calculations of crack resistance using safety factor m for the ultimate crack resistance

$$K = \frac{I_C}{m} \qquad \text{(for } \sigma_C = const \text{)}$$

(3)

Introduction of such safety factor m means shift of the diagram of crack resistance downwards, along the axis of stress intensity factor K. The initial failure assessment diagram is transformed into the admissible diagram of crack resistance which can be used now for calculation of admissible crack lengths (at matching admissible stress). Thus one equation provides calculations suitable for both stress and crack presence.

The safety factor for ultimate crack resistance *m*, unlike the general safety factor *n*, is not regulated, therefore it is reasonable (because of the lack of other possibilities) to define an admissible size of crack-like defects from a condition that the safety factor for crack resistance *m* is equal to safety factor *n* for general strength

$$n = m\,.$$

(4)

Adoption of this condition leads to the admissible diagram of crack resistance that appears geometrically similar to the critical one (line 3)

$$I_{C\,adm} = I_{C\,adm}(\sigma_{adm}) = \frac{I_{c\max}}{n}\sqrt{1-\left(\frac{n\sigma_{adm}}{\sigma_u}\right)^{q}} \qquad (5)$$

A crack size l_{adm}, at matching loads σ_{adm}, can be found from the equation

$$K(\sigma_{adm}, l_{adm}) = I_{C\,adm}(\sigma_{adm}) \qquad (6)$$

The right-hand side of this equation reflects a known line in a plane $K - \sigma$, and the left-hand side – a straight line with a slope depending on a crack length. The graphical solution of this equation is possible [2]. We note that on the abscissa axis of the crack resistance diagram it is possible to use the parameter reflecting design load parameter (for example, pressure) instead of the stress.

In conclusion, let us note that the so-called R6 two-parameter fracture criterion is adopted abroad which latest version looks (in our notation) like [7]

$$\frac{I_C}{K_C} = \left[1 - 0{,}14\left(\frac{\sigma_C}{\sigma_T}\right)^2\right]\left[0{,}3 + 0{,}7\exp\left(-0{,}65\left(\frac{\sigma_C}{\sigma_T}\right)^6\right)\right] \quad \text{at} \quad \frac{\sigma_C}{\sigma_T} \le \frac{\sigma_F}{\sigma_T}\ ,$$

$$\frac{I_C}{K_C} = 0 \quad \text{at} \quad \frac{\sigma_C}{\sigma_T} > \frac{\sigma_F}{\sigma_T}\,.$$

Here $\sigma_F = (\sigma_T + \sigma_B)/2$ is introduced. The ultimate crack resistance diagram (failure assessment diagram) built according to this formula is resulted in line 2 of Fig. 1. Considerable conservatism of this estimation in the most actual area of crack lengths is visible (divergence with experimental load and with a limit of crack resistance is more than twice). The physical essence of diagram R6 is not obvious. At the same time the sense of an ultimate crack resistance is clear: it is the stress intensity factor computed for the maximum load (like definition of ultimate strength) and withstood by the sample with a crack (for equal samples but with different crack lengths).

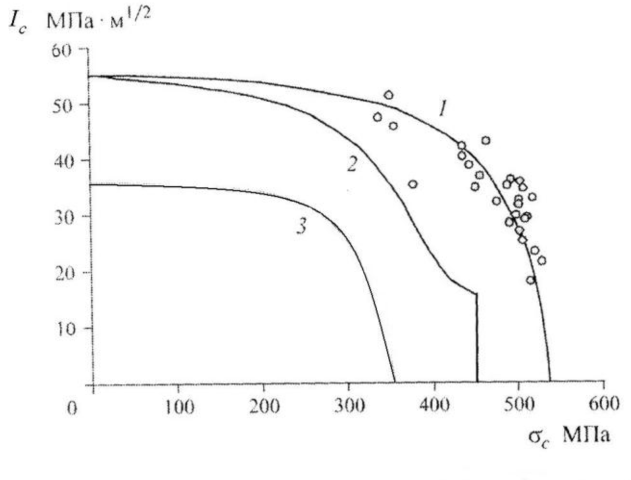

Figure 1. Failure assessment diagrams

Summary

Thus, the two-fold role of the ultimate crack resistance has been shown. This characteristic can be used for sampling and for estimating materials and production methods. The ultimate crack resistance can be also employed for safety strength calculations of structural components with cracks.

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